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Performance of Hearing Protectors in Impulse Noise

K. Buck
French German Research Institute
BP 34, 5 rue du Général Cassagnou
68301 Saint-Louis CEDEX
France

Summary

The present paper describes the problems that may occur when hearing protectors, usually designed for industrial noise environments, are used in military impulse noise. The military impulse noise environment is described as well as the different types of passive and active hearing protectors and the used measurement procedures. The different mechanisms that may alter the effectiveness of different types of hearing protectors, as well as the global efficiency when submitted to high level impulse noise, will be shown.

Introduction

The current standard in the industrial community for the evaluation of hearing protectors, uses the threshold of hearing as a reference. This method, called REAT (Real Ear At Threshold), measures the threshold of hearing with and without a protection device, and the difference is defined as the so called IL (Insertion Loss). As no other normalized methods are available, the military community has used the same methods for the evaluation of their protection devices. However, the military noise environment may differ a lot from such found in workshops. Especially the noise of weapons can hardly be compared with noises found in the civilian environment. Weapon noise may expose the soldiers to peak levels as high as 190 dB. If the performance of a protection device is evaluated at threshold, this means, that the found values have to be invariant for an amplitude range of more than 160 dB, (for an amplitude that may vary in a range of 1 to 10^8 or more, if the most powerful weapons are considered). As it is not reasonable, to think that no secondary effects or nonlinearities may be found through such a big range, the performance of hearing protectors, should not be only evaluated at low levels, but also at levels and for signals, that are typical for the military environment. To do this, the evaluation procedures and the associated tools have to be adapted to the high levels to which the devices will be exposed. As each different type of hearing protector may respond in a different way to impulse noise at very high levels, it is important to understand the specificities of the different protecting devices.

Impulse noises in the military environment

The military noise environment is usually not very silent. The rush to higher performance for tanks,

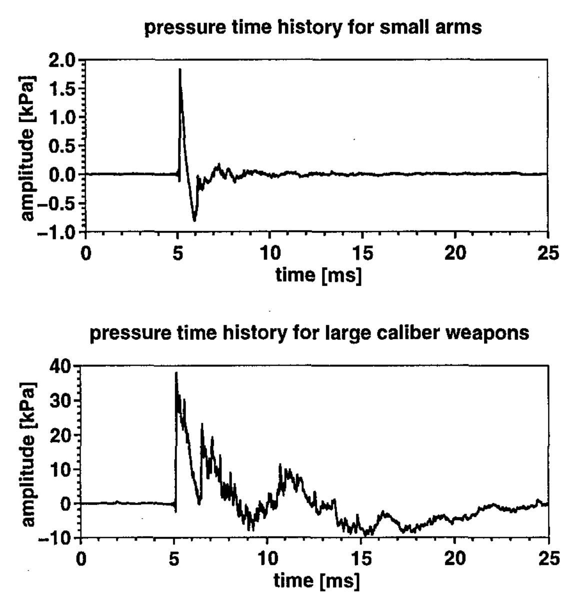

Figure 1 : Typical time pressure histories for small arms (A) and large caliber weapons (B)

airplanes and weapons leads to more noise. The noise level to which the crew members of a tank are exposed is in the range of 110 dBA. Technical staff that has to stay near fighter airplanes is even exposed to higher levels (up to almost 140 dBA). The impulse noise created by modern weapons, may range from 150 dB peak pressure level with a

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duration of 0.5 ms for handguns, to almost 190 dB and a duration of some milliseconds for howitzers and mortars. In figure 1 two typical pressure time histories due to the firing of weapons are shown. The upper curve (A) shows a small arm's (e.g. rifle or handgun) signature. The maximal pressure of this type of weapon

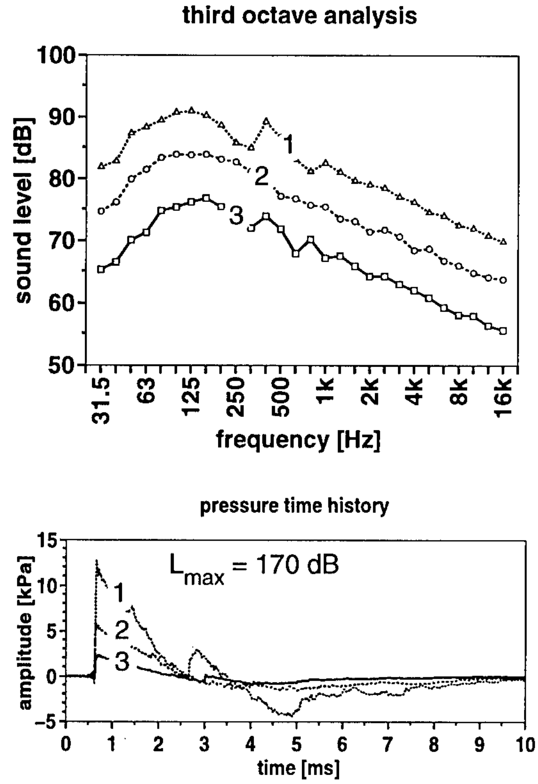


Figure 2 : Third octave analysis for the different weapon noises with the same A-duration (upper graph) and different amplitudes.
The corresponding time signals are drawn in the lower graph

is between 150 dB and 170 dB at the ear of the user. The A-duration of the signature of such weapons is about 0.3 ms to 0.6 ms. In the lower frame (B), the pressure time history of a large caliber weapon is drawn (e.g. howitzer or mortar). For these weapons, the maximal pressure may exceed 180 dB, and the duration is in a range between 2 and 4 ms. The spectral compositions of these noises are displayed in figure 2 and 3. We can see in these figures, how the spectral composition depends on the pressure time history of the signal. Figure 2 shows that, for constant duration and for different amplitudes, only the level of the different components changes but not the envelope of the third octave analysis. For impulse noises having the same peak pressure, but different A-durations (figure 3), the high frequency components of the spectrum stay the same, but the low frequency energy of the spectrum becomes, with growing duration, more important. These figures (2 and 3) show that the spectral

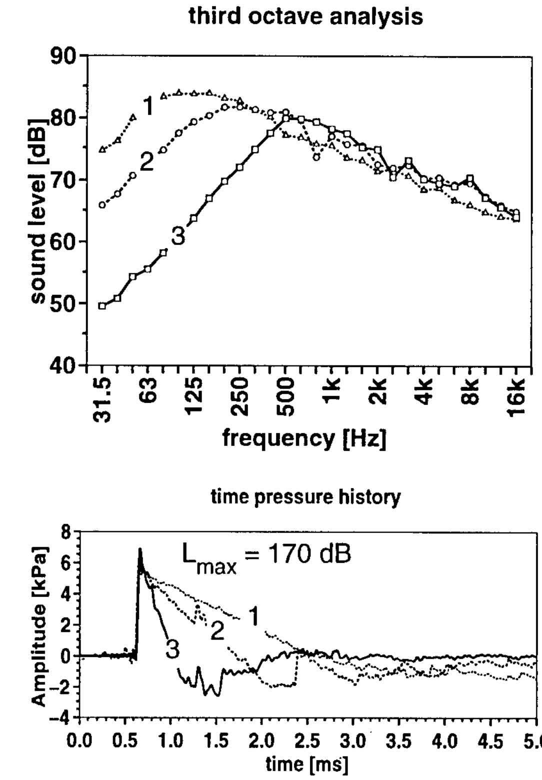


Figure 3 : Third octave analysis for the different weapon noises with the same amplitude (upper graph) and different durations. The corresponding time signals are drawn in the lower graph.

distribution of the energy, for shock waves with identical peak pressures, is the same for all frequencies higher than 1 kHz (if we consider realistic weapon noise) and extends towards the lower frequency bands if the duration of the impulse becomes longer. For waves with a constant duration, change in amplitude only affects the amplitudes of the different spectral components.

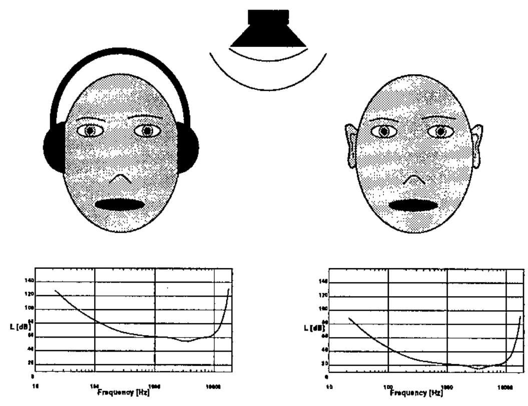
The time pressure histories in the two figures show, that the rarefaction phase of the pressure signals is usually about one third of the maximal overpressure, but its duration may be two to three times longer, and this part of the wave may be very important for the responses of hearing protectors at very high impulse noise levels.

The evaluation method for hearing protectors in impulse noise

The evaluation of hearing protectors for the use in continuous noise is well known, and normalized in different standards. There are mainly two different types of evaluation procedures of hearing protectors :

- subjective methods: the subjective response of human subjects is needed to obtain result,
- objective methods: the result is obtained by physical noise measurements.

Subjective methods:
The best known of the subjective evaluation methods for hearing protectors is the so called REAT (**R**eal **E**ar **A**t **T**hreshold) method. The principle (figure 4) of this



$$IL = L_{Th\ protected} - L_{Th\ unprotected}$$

Figure 4 : Calculation of the insertion loss with the REAT method

method consists in measuring the threshold of hearing of a subject in free sound field with and without a hearing protector. The level difference between the measurement with protected ears, and the measurement of the unprotected ears is defined to be the **I**nsertion **L**oss (IL). This method is widely accepted in the industry. As the behaviour of a hearing protector in 180 dB peak pressure level impulse noise is not the same than in continuous noise at threshold, the REAT method should not be used for the evaluation of material due to work in military impulse noise environments.

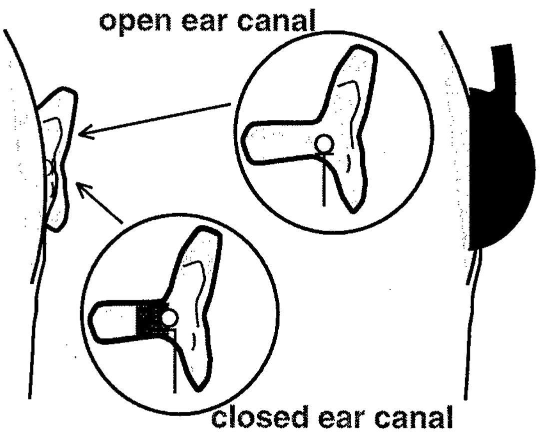
Objective methods:
Objective methods determine the insertion loss by the means of physical measurements. There are two main types:

- the MIRE (**MI**crophone in **R**eal **E**ar) method,
- the method using an ATF (**A**rtificial **T**est **F**ixture) or "artificial head".

The MIRE method consists basically (figure 5) in measuring the pressure at the entrance or inside the ear canal of a human subject. There are different ways how the microphone may be placed in near the entrance of the ear canal:

- placing it with adequate means near the entrance and leaving the ear canal open. This method has the advantage to preserve the input impedance of the ear canal, what might be important for the evaluation of ANR devices.
- fixing the microphone on top of an ear plug which will be inserted. This method is usable for high noise levels because of the protection of the subjects ear by means of the ear plug.

The evaluation of hearing protectors with this method has the advantage of taking into account more



$$IL = L_{unprotected} - L_{protected}$$

Figure 5 : The MIRE method to determine the IL

accurately the soft tissue surrounding the ear and the morphological differences between subjects. However the evaluation of earplug is not possible by means of this method and still, there are ethical problems in exposing human subjects to levels that may damage the hearing organ.

The limitations of use that are found with the MIRE method, are not applicable for artificial heads (ATF), as artificial heads are equipped with ear simulators and a microphone at the place of the drum. ATFs also allow the measurement of ear plugs and measurements with the open ear up to the physical limits of the transducers in the ear. Moreover, as the ear simulator reproduces

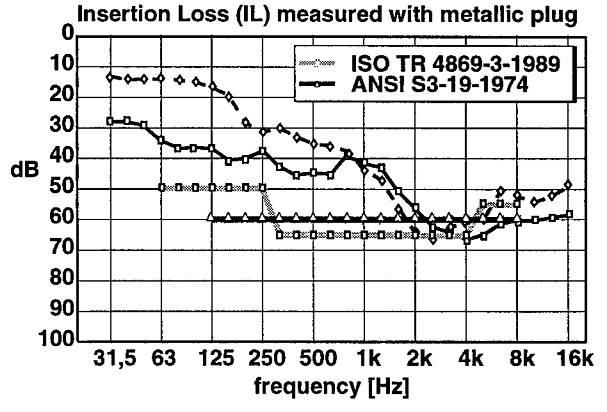


Figure 6 : Acoustic insulation of two commercially available artficial heads compared to the required values of ISO and ANSI

the acoustical impedance at the drum comparable to human data, ANR headsets may be tested without any problems. Although the method is valid for the

evaluation, the artificial heads that are available off the shelf may produce problems in use. Those devices, usually developed for the recording of music or to evaluate communication devices, lack usually of acoustical insulation when the outer ear is blocked. This means, that secondary sound and vibration passes do not allow acceptable attenuation measurements with protection hearing protectors and impulse noise. Figure 6 illustrates this problem. The 2 measured artificial heads were far from fullfilling the requirements of the ANSI or ISO standards, especially in the low frequency range it would not be possible to evaluate any ear plug as the measured attenuation would be the insertion loss of the head and not the insertion loss (~30-40 dB) of the ear plug.

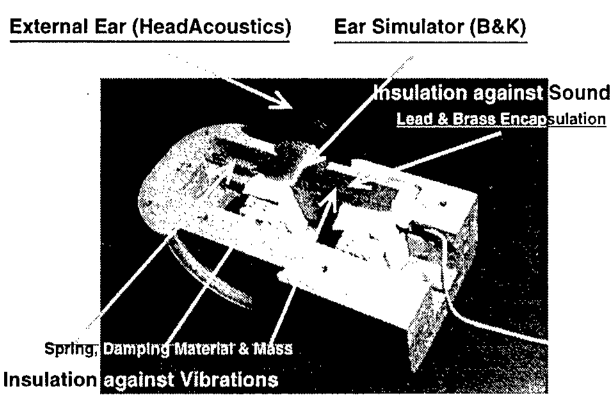


Figure 7 : Acoustically insulated and shock absorbing mount of the measurement elements

As there was no immediate solution to resolve this problem with commercial ATFs, we developped at ISL an artificial head with the aim to fullfill the standards for the whole frequency range. In order to obtain this, the acoustic insulation and shock absorbing mount of the measuring element have been especially looked at. The figure 7 shows the open head and its elements. As far as it was possible, we used elements that were commercialized (e.g. external ear from Head-Acoustics; Ear simulator - B&K). The final product, and its performance (figure 8) were fully satisfactory. The acoustic insulation was more than 60 dB for all frequencies, what complies with the ISO/ANSI requirements.
To obtain the insertion loss of a hearing protector, we proceeded in the same way as already described for the MIRE method (fig 5): two measurements were made, one with and one without the hearing protector; the difference between these measurements being the IL.

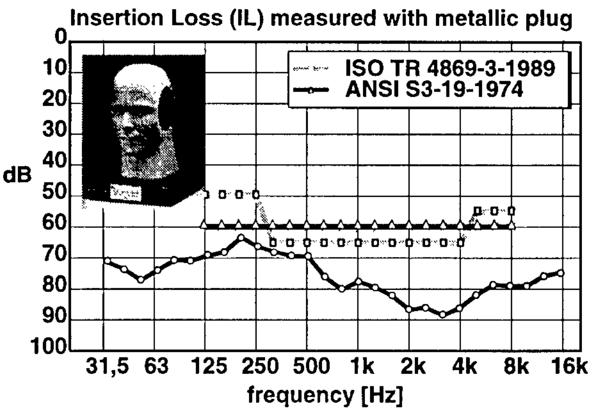


Figure 8 : Acoustically insulated and shock absorbing mount of the measuremet elements

Generation of the impulse noise:

As it is pratically impossible to generate impulse noise with maximum level of 190 dB with loudspeakers, or other electrical devices, there are only two possibilities left:

- shots with real ammunition,
- detonation of explosives.

As real shots are very expensive and involve many personal, we use for our tests explosive charges (Plastit ®) of different weights, being situated at different distances from the artificial head. This technique

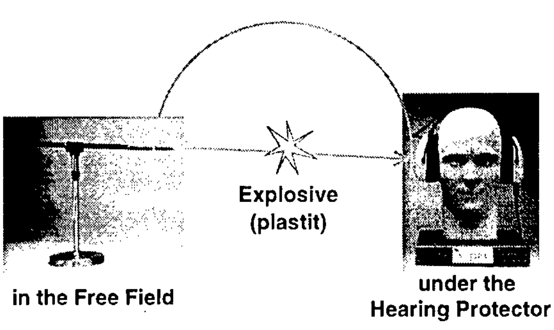


Figure 9 : Setup for a measurement to evaluate hearing protectors with high level impulse noise

allows us to have well defined acoustical waves in the free field with peak pressures between 150 dB and 190 dB and different A durations (0.4 - 2 ms). Figure 9 shows how the artifical head and the free field microphone are situated. The distance from the explosive charge is variable, depending on the requirements (signal duration and peak level).

The different types of hearing protectors

As far as the hearing protectors are concerned, there are two basic types of protectors:

- Ear muffs:
  This type of hearing protector insulates the ear from outside noise with a barrier shell sealed by a circumaural seal of elastic material to the head,
- Ear plugs:
  In this case the insulation is realised by occluding the external ear canal by means of soft acoustically insulating material.

These two types of hearing protection are shown in the

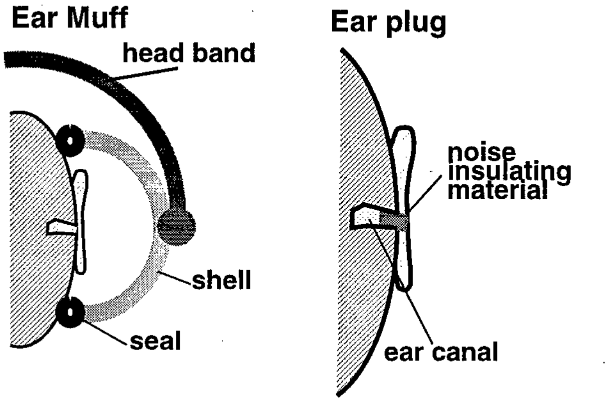


Figure 10 : The two main types of hearing protectors.

figure 10. Depending on the noise and the tasks of the wearer of the protection device, different types have been derived from these basic principles.

Ear muffs: The noise insulation of an ear muff is mainly determined by the following variables:

- the mass of the shell + seal + effective part of the head band,
- the constants of the material of the seal, e.g: density, stiffness, damping ...
- the material constants of the shell, e.g.: density, stiffness, damping ...
- the residual volume underneath the shell and the acoustic damping inside this volume,
- the overall damping of the system, including head band, seal and shell.

Typically, the insulation of an ear muff has to be considered for two frequency ranges where the

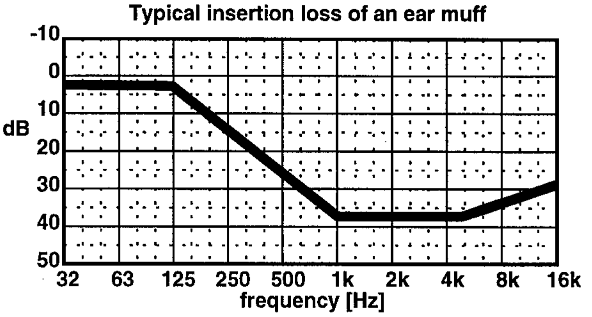


Figure 11 : Typical attenuation of an ear muff

different parameters, enumerated before, govern the attenuation behaviour. Figure 11 shows these different parts. For low frequencies, up to about 1 kHz, an ear muff acts mainly like a low pass filter. The simplified

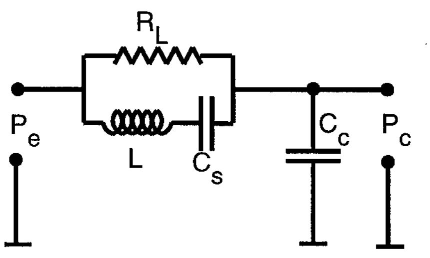


Figure 12 : "very" simplified electrical equivalent of an ear muff for low frequencies

electrical equivalent of the behaviour of the ear muff at low frequencies is shown in the figure 12, where

P_e corresponds to the pressure outside,
P_c to the pressure underneath the muff,
L to the equivalent mass of one earcup,
C_s to the compliance of the seal,
C_c to the compliance of the air volume, underneath the cup,
R_L resistance of the leak in the seal.

We can see in this figure, that the predominent parameter for the low frequency attenuation, is the residual volume under the shell. The bigger this volume (C_c) for constant L,C_s and R_L, the lower will be the residual pressure P_c. The transient phase (about 150 Hz in figure 11) is governed by the mass (L) and the compliance of the seal (C_s) of the protection device. For the frequency range up to 500 Hz the most important parameters are :

- the volume of the hearing protector,
- the mass of the protector,
- the compliance of the circumaural seal,
- the leakage through the circumaural seal.

This means: To get a good insertion loss at low frequencies, we need to design a ear muff with a very big volume, that is very heavy and equipped with a very unflexible but perfectly sealing circumaural seal.
In figure 13, a electrical equivalent of the ear muff for medium frequencies is drawn. This range (1 to 4 kHz) is mainly depending on the material constants of the shell (compliance C_P) and the volume of the shell. Here again, a large ear cup would give a better

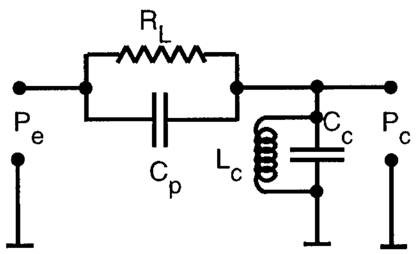


Figure 13 : "very" simplified electrical equivalent of an ear muff for medium frequencies

insulation. However, as bigger cups also might be more flexible, this design approach is not always reasonable, they also will have more weight, and so the user probably will not accept the device. If the inside of the ear muff is not damped, the mass of the air (L_c) and the compliance of the air (C_c) will tend to oscillate. For higher frequencies, as the wavelength becomes comparable to the dimensions of the muff, the inside of the protector may not anymore modeled with lumped parameters. for this case, the most important parameters are the acoustic properties of the material of the ear cup and the parameters of the damping materials inside the shell.

Active Noise Reduction (ANR) ear muffs:

As we have seen before, the low frequency attenuation with ear muffs is usually unsufficient and the parameters that can positively influence this behavior,

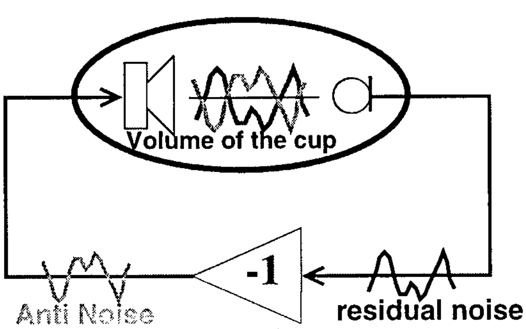


Figure 14 : simplified principel of Active Noise Reduction (ANR)

mass and volume, imped on the ergonomics and on the functionality. A possibility to overcome these limtations, is the addition of an ANR system to the passive protector. The basic principle of that technology (figure 14) is to measure the residual noise in the cavity under the ear muff and to create a noise that is in opposite phase to it. Combining the two noises, results in an attenuation. For stability reasons,

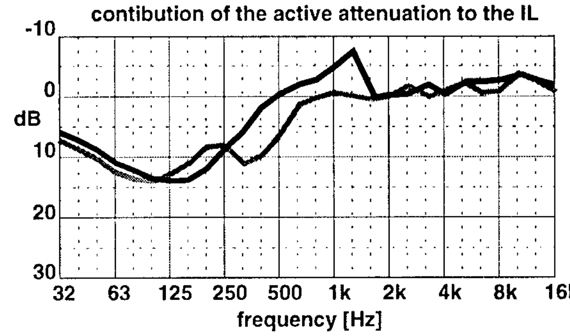


Figure 15 : Attenuation added by an ANR system to the passive Insertion Loss

this principle does not work over the whole frequency range, but only for low frequencies (Figure 15). These devices are very useful in armored cars or helicopters, where the major part of the acoustic energy is delivered in the low frequency range. For weapon noise however, these devices, may be vulnerable due to their electronics involved. This part however will be described in a later paragraph.

Talk through systems:
For working places, that need verbal communication between different people, so called "talk through" hearing protectors have been designed. In this type of

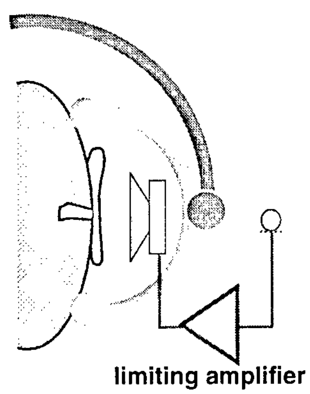


Figure 16 : principle of a "talk through" system

device (figure 16), the external sound is capured by a microphone and fed into the cavity of the hearing protector. To avoid hearing damage due to excessive noise these systems have an amplitude limitation in the amplifier of the telephone inside the cavity. Therefore this protector type may be considered like passive ear muffs for levels that exceed the limitation of the electronic system.

Ear Plugs:
The noise insulation of an ear plug is mainly determined by the following variables:

- the mass of the earplug,
- the constants of the material of the ear plug, e.g: density, stiffness, damping
- the interface between the earplug and the ear canal, e.g. shearstiffness,
- the residual volume under the plug and its acoustic damping

The typical attenuation of an ear plug is shown in figure 17. It is shown, that for a properly fitted ear

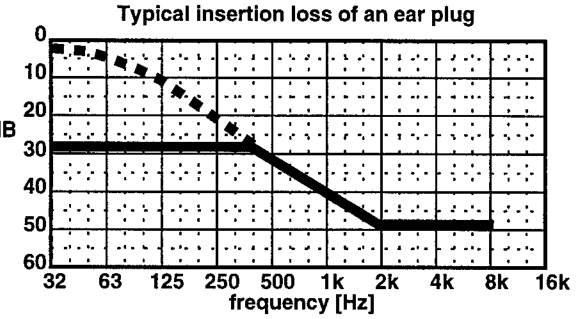
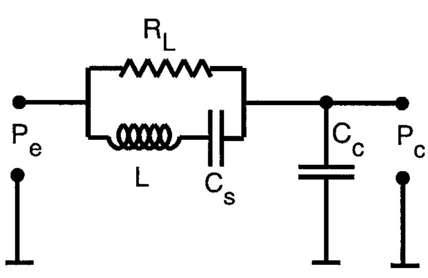


Figure 17 : Typical insertion loss of an ear plug (solid line). The broken line represents the typical IL of a badly fitted plug

plug, the attenuation at low frequencies is already very good. However, if the fitting is not well done, the insertion loss in the low frequency range will be



R_L leakage

L mass of the plug

C_s shear compliance between plug and skin

C_c compliance of the air the residual volume of the ear canal

Figure 18 : "very" simplified electrical equivalent of an ear plug for low frequencies

degraded (dashed line). This effects become understandable, if we look at the simplified electrical equivalent (figure 18). Although it is the same than this of an ear muff, the values of the different components are largely different and affect the behaviour. Especially, as the compliance of the residual volume (C_c) is very small, any leakage will affect the low frequency behaviour very strongly as shown in the figure 17 (difference between well and badly fitted ear plug).

For higher frequencies (>2 kHz), the attenuation of an ear plug is mainly determined by the absorption qualities of the used materials.

Non linear ear plugs:
For many tasks and environments within the military community it is often very important that the soldiers are able to communicate and to hear and interpret the acoustic environment. But these soldiers, also have to be protected against weapon noise, as this could lead to hearing imparement, and so again to communication problems and misinterpretation of the acoustic environment.
In those cases, non linear ear plugs are a good choice. This type of protector only protects against high level noise, and allows almost an unaltered hearing in the

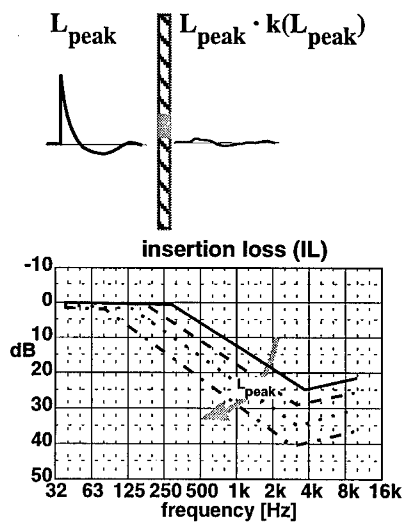


Figure 19 : principle of non linear ear plugs

case of moderate sound fields. The main principle (figure 19) is based on nonlinear acoustic behaviour of small orifices. The acoustic resistance of such orifices is a function of the gasflow through the orifice, and grows with increasing flow. So, for small amplitudes of the noise, the orifice is almost acoustically transparent, whereas for high level impulses, it becomes almost acoustically closed.

Performance in high level impulse noise

Ear muffs:
Ear muffs may be considered to be linear up to a peak pressure level of about 150 dB. Up to this level, the IL measured at threshold may be valid also for impulse noise. For higher levels this is not any more true, because some of the elements described in the

electrical equivalent are no more considered as linear.

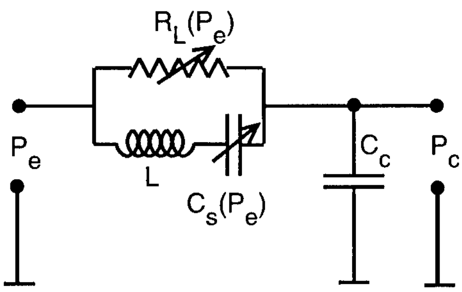


Figure 20 : "very" simplified electrical equivalent of an ear muff for low frequencies for high peak pressures

The value of some of the elements has now to be considered to be a function of the pressure input (pressure in the free sound field). These elements are shown in figure 20. The compliance of the circumaural seal will be modified differently for the overpressure and the rarefaction phases of the pressure signature.

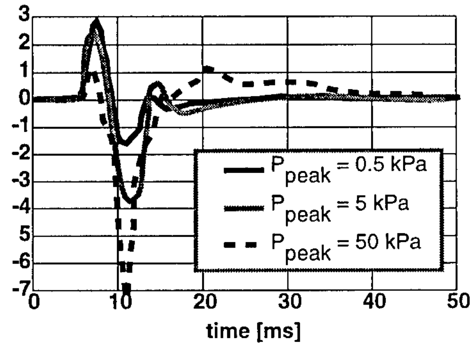


Figure 21 : normalized response under an ear muff for different impulses with the same A duration and different peak pressures.

During the overpressure phase it will become less compliant due to compressibility limits in the material. In the rarefaction phase, the ear cup will be torn away from the head, and that will lead to much higher compliance. The same is true for the leakage (R_L). During the overpressure this acoustical resistance will become bigger and so provide additional isolation, whereas during the rarefaction phase the seal will become less tight and the protection is less effective. These effects can be see in figure 21. The normalized positive peak pressure of the impulse under the ear cup becomes smaller with growing external amplitude, whereas the negative peak becomes more and more important. This leads, if the peak-to-peak amplitude is concerned to less protection with growing free field peak pressures. This decrease can also be observed in figure 22, where the insertion loss of the ear muff for the three different cases is represented. Especially in the low frequency region as well as in the region around 1 to 2 kHz a strong decrease of the

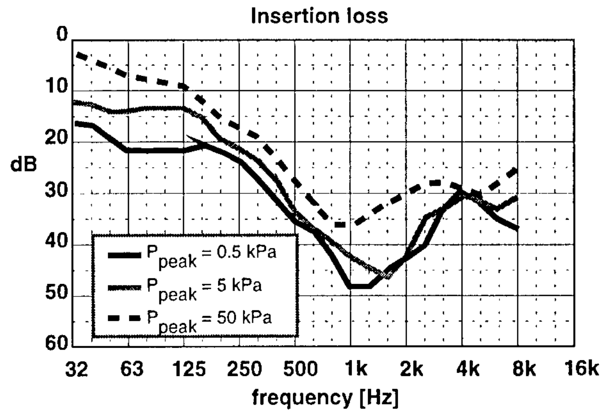


Figure 22 : insertion loss of an ear muff for impulses of the same A duration 2 ms and different Peak pressures

effectiveness (more than 12 dB) of the protector can be observed. These effects depend very much about the configuration of the hearing protectors, and one of the main factors is the force of the head band that holds the protection device. If this force is to small, the amplifying effects during the negative phase of the impulse will appear earlier. The material of the seals also is an important factor. These seals are often made with strongly damped material, in order to get a better insulation in the low frequencies. For very high levels however, these materials cannot expand fast enough, and will allow a bigger leakage than less damped seals.

ANR ear muffs:

For very high levels, as described before, the mechanisms and effects of ANR devices will be the same. However, the contribution of the ANR to the insertion loss as shown in figure 15 will level off at the moment when the needed pressure cannot be any more

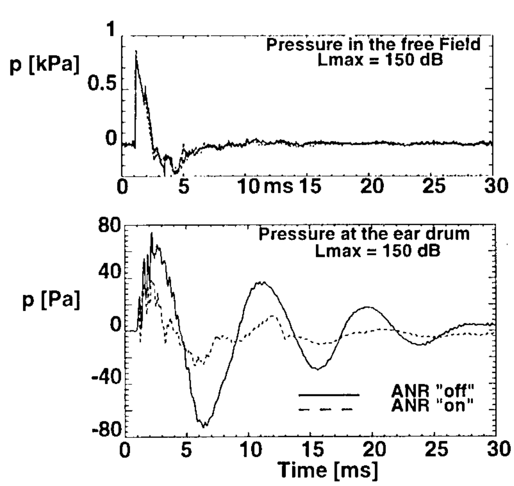


Figure 23 : Effect of ANR on an impulse noise

provided by the loudspeaker of the system. Figure 23 shows how the ANR sytem acts on the impulse under

the ear muff. For this signal, 150 dB peak pressure and 2 ms of A duration, the ANR system is still able to provide some attenuation. At the peak level of 170 dB

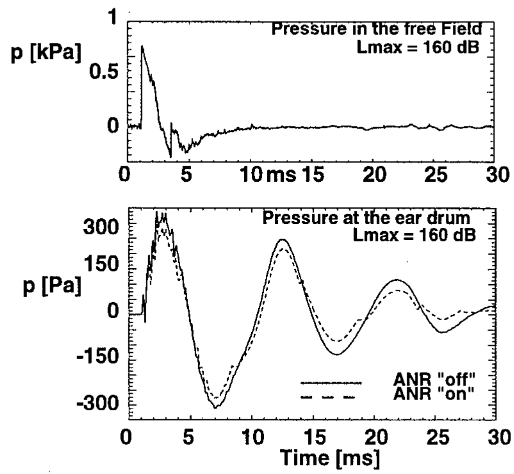


Figure 24 : Effect of ANR on an impulse noise

shown in figure 24 the ANR is not anymore able to contribute some attenuation. As these strong impulse noises, may affect (at least temporarily) the transfer function of the electroacoustic system of the ANR hearing protector it might be possible, that these systems become, for a short time after the impulse, instable.

Talk through ear muffs:
As talk through systems are designed to act like passive ear muffs for levels that are above the saturation level of the amplifier, the same effects as for standard ear muffs will apply. However, if the saturating electronic system is not well designed, undesired noises may arise in the moment of the arrival of an impulse noise.

Ear plugs:
The insertion loss of ear plugs is contrary to that of ear muffs affected only by very high level impulse noises. This can be seen on the figure 25. Although the peak pressure level varies from 150 dB to 190 dB, the variations in the insertion loss does not show variations of more than 5 dB, whereas the IL measured with ear muffs may vary for more than 15 dB. This is mainly due to the fact, that the non linearities that allow the leakeage resistance of the seal to decrease, are not present, as the ear plug is fixed by friction to the ear canal and not by a stiff head band as it is the case with ear muffs. This mechanism tends rather to limit the excursion of the plug in either direction. However, if ear plugs are not well fitted it may well be, that leakage will occur.

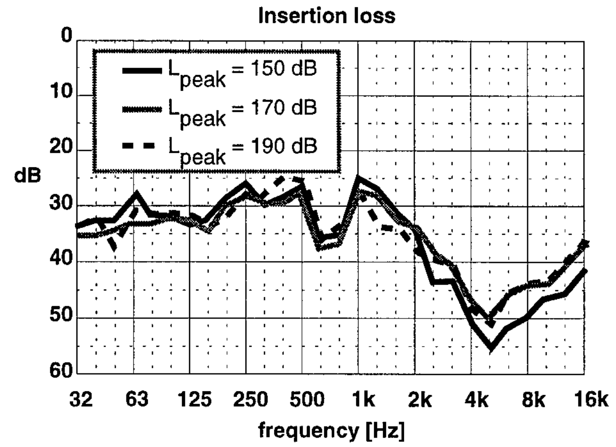


Figure 25 : nsertion loss of an ear plug for impulses of the same A duration 2 ms and different Peak pressures

Non linear ear plugs:
The design of nonlinear earplugs is made in a way, that the insertion loss of the protector should increase substantially with increasing peak pressure of the incident impulse noise. The figure 26 shows very well

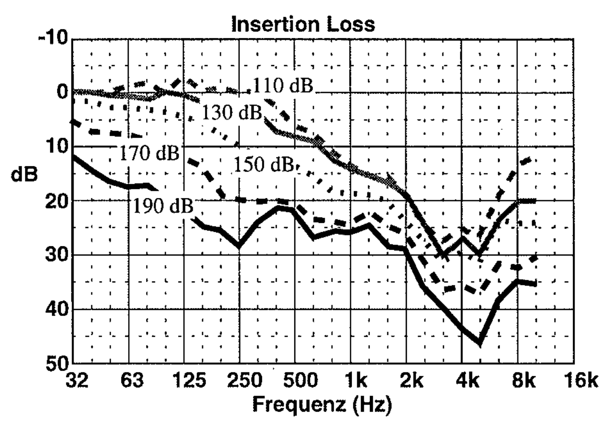


Figure 26 : Insertion Loss of the non linear ear plug developed at the ISL for impulse noise with different peak pressures

the non linearity of this protection device. For signals with a peak pressure level of 110 dB, the Insertion Loss does not exceed 30 dB for any frequency and for spectral components lower than 500 Hz the non linear plug is practically transparent (well fitted standard ear plugs have an attenuation of about 30 dB in this frequency range). For the impulse noise with highest levels (130 dB - 190 dB) the attenuation increases gadually over the whole frequency range. Finally at the peak pressure level of 190 dB, the attenuation over the whole frequency range is almost the same than a good linear earplug. The reduction of the peak pressure of the free field compared to the peak pressure at the microphone of the artificial head follows the same scheme. At a peak pressure level of 110 dB, the reduction of the peak is 8 dB. Passing to higher levels,

this value increases to reach finaly 25 dB for a peak pressure level of 190 dB.

Conclusions

The acoustic environment of the soldier is very different to the noise that will be usually found in the industry. However many of the evaluation standards and measurement procedures are made for this civilian environment. Using these methods would mean to ignore the specificity of the surrounding where the soldier has to work and where unadapted equipment may very well be a reason for operational failure. To avoid this the hearing protection should be evaluated with signals, that really occur, because only these tests allow to be sure that the personnel is protected for all possible cases.

The evaluation of different types of hearing protectors has shown, that the protection that is given for low levels, is not the same than the protection for very high level impulse noise. Especially ear muffs are very dependent of certain design citeria, and so, some very effective features for low levels or continuous noise (e.g. low application force combined with seals made with material having a strong damping) may impede on the protection against high levels. We have seen, that the Insertion Loss may decrease by 15 dB for the highest levels, (compared to the lowest level).

If new types of hearing protectors like ANR systems or "talk through" protectors are evaluated, there is not only the Il to be looked at, but also the behaviour of the electronics when it is driven into saturation. ANR sytems are well able to add extra attenuation to impulse noise of "low" levels, for high levels however, there is always a risk of instabilities.

If no electronic communication requirements are needed, ear plugs may be the first choice for the protection against very high levels of impulse noise. Standard ear plugs may almost be considered as linear protectors for the whole range of levels. Their characteristics change only very little over the whole range of impulse noise levels. However, it is always necessary to have them inserted proprely in the ear canal. If not, the protection capabilities degrade. If verbal communication and acoustic reconaissance of the surrounding area are important, the most interesting way to protect a soldier is non linear ear plugs. These devices are the only protecting devices, that have a better insertion loss for higher levels. They always give the needed protection in the case of a sudden shot, but allow good communication. As these protectors are designed to work only for impulse noise when the user is in a quiet surrounding, they are not suitable to protect against continuous noise. The evaluation of these devices has to be made with impulse noise, because they need noise to work. If these devices are evaluated with standardized methods the results will not reflect their real protection capability in impulse noise.

The protection capability of any type of hearing protector is, to some extent, dependent on the type of signal it is exposed to. It is therefore important to evaluate with signals they will be used for and not with signals that have no relevance.

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